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### Version of attached file:

Accepted Version

### Peer-review status of attached file:

Peer-reviewed

### Citation for published item:

Wang, Xiao and He, Sheng and Jones, Stuart J. and Yang, Rui and Wei, Ajuan and Liu, Changhai and Liu, Qiang and Cheng, Chunyang and Liu, Weimin (2019) 'Overpressure and its positive effect in deep sandstone reservoir quality of Bozhong Depression, offshore Bohai Bay Basin, China.', *Journal of petroleum science and engineering.*, 182 . p. 106362.

### Further information on publisher's website:

<https://doi.org/10.1016/j.petrol.2019.106362>

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Overpressure and its positive effect in deep sandstone reservoir quality of Bozhong  
Depression, offshore Bohai Bay Basin, China

Xiao Wang<sup>a</sup>, Sheng He<sup>a\*</sup>, Stuart Jones<sup>b</sup>, Rui Yang<sup>a</sup>, Ajuan Wei<sup>c</sup>, Changhai Liu<sup>d</sup>,  
Qiang Liu<sup>e</sup>, Chunyang Cheng<sup>f</sup>, Weimin Liu<sup>g</sup>

<sup>a</sup> Key Laboratory of Tectonics and Petroleum Resources (Ministry of Education), China  
University of Geosciences, Wuhan, China, 430074

<sup>b</sup> Department of Earth Sciences, Durham University, Durham, UK, DH1 3LE

<sup>c</sup> CNOOC Tianjin Co, Institution of Petroleum Exploration & Development, Tianjin, China,  
300452

<sup>d</sup> CNOOC EnerTech Drilling & Prod Co, Tianjin, China, 300452

<sup>e</sup> PetroChina Jidong Oilfield Company, Tangshan, China, 063004

<sup>f</sup> PetroChina Liaohe Oilfield Company, Panjin, China, 124005

<sup>g</sup> SINOPEC Shengli Oilfield Company, Dongying, 257000, China

\*Corresponding author, email address: [shenghe@cug.edu.cn](mailto:shenghe@cug.edu.cn)

## Abstract

Bohai Bay Basin is a Meso-Cenozoic terrestrial sedimentary basin in eastern China. Its offshore regions, including Bozhong and Liaodongwan Depressions, are favourable exploration targets which provide near a half of the petroleum reserves in the basin. Eocene Shahejie (Es) Formation and Oligocene Dongying (Ed) Formations are two important exploration targets in Bozhong Depression, and overpressure is commonly seen in Es and Ed Formations in this area. Our research examined the distribution characteristics of overpressure in the formations and suggest the main mechanism of overpressure is compaction disequilibrium due to the rapid sedimentation rates ( $\sim 500\text{m/Ma}$ ) of fine-grained sediments in this area. Also, oil and gas generation within the thick mudstones of the two formations has added the magnitude of overpressure. We investigated the reservoir quality especially primary porosity in Es and Ed formations, and their relationship with overpressure. The positive effect of overpressure on reservoir porosity preservation was validated through microscopic observations and vertical effective stress (VES) analysis. We established a quantitative model for evaluating the relationship of overpressure, pore structures, porosity, and VES. The result suggests the overpressure in the targeted formations were primarily originated from undercompaction. The overpressure kept VES from increasing and helped preserve the primary intergranular porosity. The porosity preserved by overpressure can be significantly higher than normally compacted porosity under the same condition of depth and temperature.

**Keywords:** overpressure; reservoir quality; Bohai Bay Basin; Shahejie Formation; Dongying Formation

## 1. Introduction

Reservoir quality evaluation is vital in the exploration and development of deeper targets. Pore geometry, porosity and permeability are the starting points of reservoir quality research (Pittman, 1979; Ehrenberg, 1989, 1990). Deeply buried sandstones with anomalous porosity and permeability are favourable reservoirs providing great probability for commercial production. Anomalous porosity or permeability is statistically higher than the values in typical sandstone reservoirs of a given lithology, age, and burial/temperature (Gluyas and Cade, 1997; Bloch et al., 2002; Taylor et al., 2010). The controlling factors and mechanism of porosity formation and preservation during diagenesis have long been investigated. Loucks et al. (1977) studied the reservoir qualities of Lower Tertiary Frio Formation in Texas Gulf Coast and proposed porosity in shallow reservoirs (<2500m) decrease due to compaction and cementation, however, deeper reservoirs (2500~3500m) gain greater porosities from late subsurface leaching. Bjørlykke (1992, 1998, and 2015) investigated clay mineral reactions in shales and sandstones and discussed their importance in mechanical and chemical compactions. The characteristics of clay coatings and their contribution to porosity preservation in deeply buried reservoirs have also been studied worldwide (Pittman, 1992; Ehrenberg, 1993; Hammer et al., 2010; Morad et al., 2010; Taylor et al., 2010; Maast et al., 2011; Dowey et al., 2012; Stricker et al., 2016a, 2018; Cui et al., 2017; Tang et al., 2018). Overpressure can make great impact on reservoir quality as well. Scherer (1987) looked into thirteen parameters for their influence on primary porosity in sandstones and suggested overpressure may resist the compaction process and preserve primary porosity at a rate of 2% porosity for every 6.9 MPa (1,000 psi) overpressure. Dixon et al. (1989) studied the preserved high primary porosity in deep Norphlet sandstones (20% at depths of more than 6000 m) in Alabama and proposed migration of hydrocarbons and geopressuring is one of the major factors of the preservation. Ramm et al. (1994) predicted the porosity in Norwegian Continental Shelf and summarised the positive correlation between fluid pressure and porosity. This positive correlation between porosity and overpressure has been proved in the researches of the central North Sea (Kugler et al., 1990; Haszeldene et al., 1999; Lander and Walderhaug, 1999; Osborne et al., 1999; Yardley et al., 2000; Lubanzadio et al., 2002; Wilkinson et al., 2006; Goultly et al., 2012; Nguyen et al., 2013; Grant et al., 2014; Sathar and Jones, 2016; Stricker et al., 2016b; Oye et al., 2018; O'neil et al., 2018).

Pleistocene Dongying Formation (Ed) and Eocene Shahejie Formation (Es) are two deep targets (>3000m) in the offshore regions of Bohai Bay Basin, in which overpressure is commonly seen (Wang et al., 2016; Liu et al., 2016, 2017, 2019). In this work, the characteristics of overpressure in Es and Ed are summarized, and the relationship between

overpressure and anomalous porosity is investigated through the comprehensive analysis of wirelines, microscopic features, vertical effective stress, and test data including DST, core porosity and permeability.

## 2. Geological settings

### 2.1 The structural settings

Bohai Bay Basin, also known as ‘Bohai Basin’ (Allen et al., 1997, 1998), is a “young” sedimentary basin in eastern China. The recently published papers tend to reach an agreement that Bohai Bay Basin is a rift basin reformed by strike-slip faulting (Cai et al., 2001; Hu et al., 2001; Qi, 2004). The structural frame of the offshore regions, having the area of about  $4.7 \times 10^4$  km<sup>2</sup> and currently covered by the Bohai Sea, is formed by Cenozoic tectonic deformation which is a part of Himalayan tectonic movements (Mi and Duan, 2001; Xu et al., 2002; Xu et al., 2006) and consists of two major depressions: Bozhong and Liaodongwan Depressions (Fig. 1). Bozhong Depression is located in the south and in its centre formed the thickest sedimentation (>11 km). Significant extension began in Bozhong Depression at approximately 43 ~ 45 Ma ago. This syn-rift stage formed the thick layers of Es and Ed Formations and ceased at the end of Oligocene. Then the post-rift thermal subsidence stage have been taking place since the Miocene (24.6 Ma to present) (Cai et al., 2001; Qi, 2004; Gong, 2004; Zhou et al., 2010).

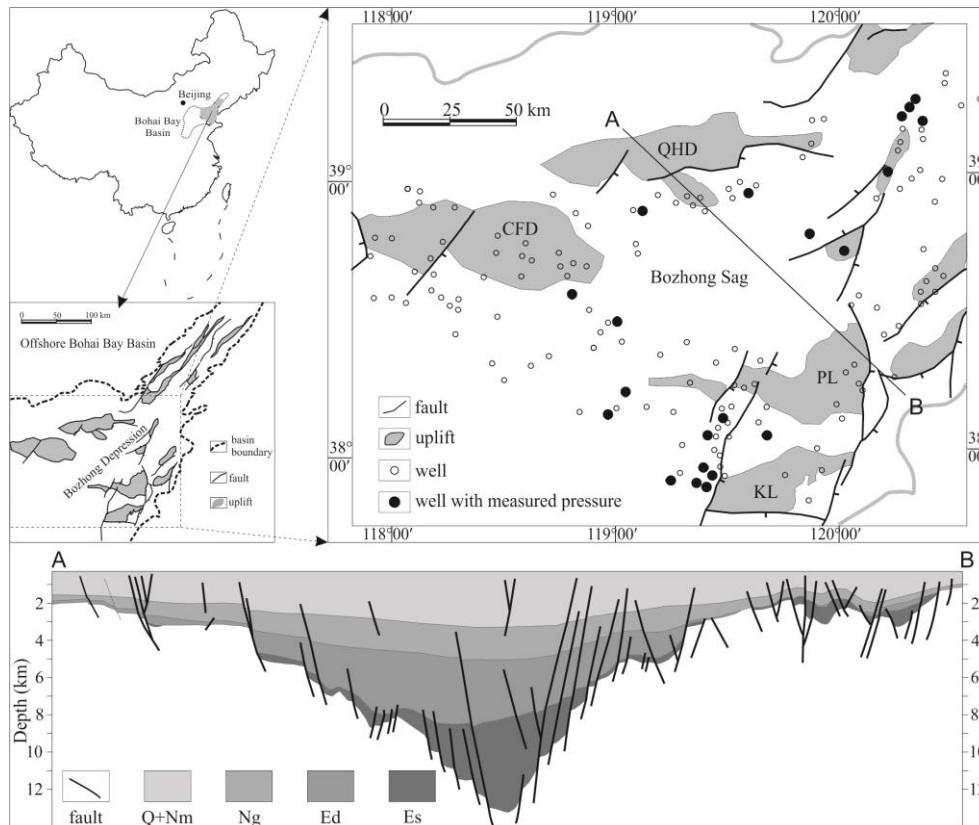


Figure 1. Location and structural distribution of Bozhong Depression.

## 2.2 The stratigraphic settings

The strata revealed by drilling in Bozhong Depression are (from bottom to top): Anz, Paleozoic (Pz), Mesozoic (Mz), Paleocene-Eocene Kongdian Formation (Ek), Eocene Shahejie Formation (Es), Oligocene Dongying Formation (generally accepted labelled as Ed), Lower-Neocene Guantao Formation (Ng), Upper-Neocene Minghuazhen Formation (Nm), and Quaternary (Qp) (Fig. 2). Their total thickness reached 12000m (39372 ft) in the Bozhong Sag which is the deepest sag of Bozhong Depression, among which Es and Ed Formations take up more than 70%. Es and Ed Formations are delta-lacustrine formations and form two main series of source rock and reservoirs.

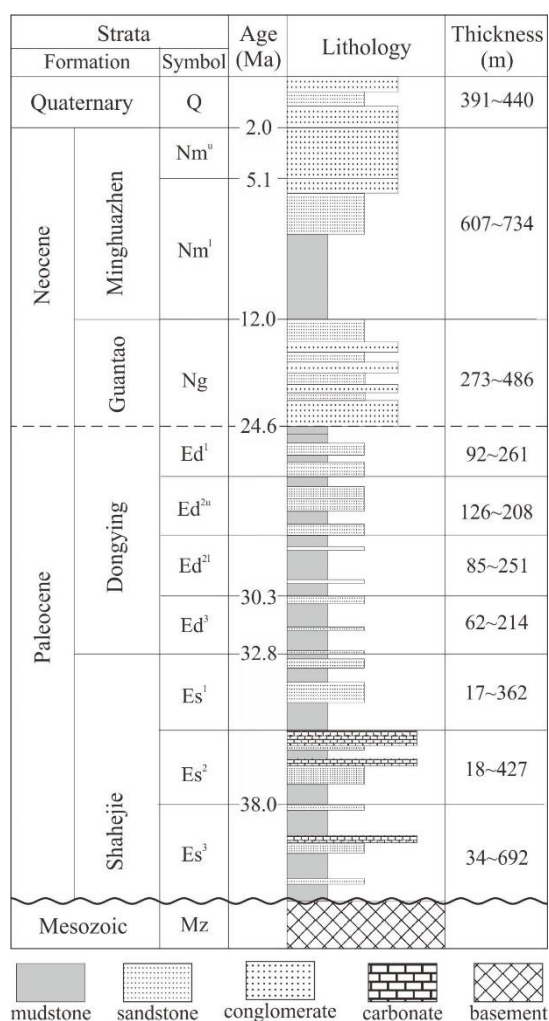


Figure 2. Summarized stratigraphic columns of offshore Bohai Bay Basin.

## 2.3 The burial and thermal maturity history

Es and Ed Formations are of great thickness in Bozhong Depression. Sedimentation rates of these two formations are relatively high, generally over 200m/Ma, highest reached 525m/Ma. The rapid sedimentation of Es and Ed made it difficult for pore pressure in and underneath Lower Ed to dissipate along the burial. This disequilibrium compaction directly caused the

over pressures in Es and Ed Formations. The estimation of pore pressure evolution shows the overpressure (pore pressure extracts hydrostatic pressure) primarily emerged during the deposition of the second member of Ed Formation (Fig. 3).

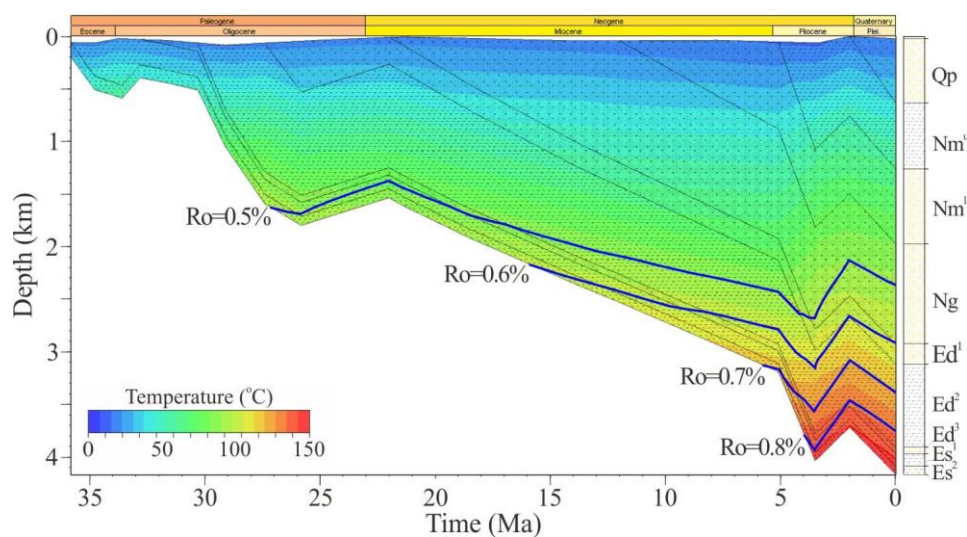


Figure 3. Burial and thermal history of Bozhong Depression.

### 3. Data and method

We used thin sections observations, core measurements, pore pressure data, and microscopic images to investigate the sandstone composition, reservoir property, pore pressure characteristics, and microscopic features corresponding to different pore pressure conditions. Basin modelling and VES analysis were used in analysing the origin and effect of overpressure.

194 sandstone thin sections of Ed and Es Formations were observed. Grain size and sorting data were obtained by measuring the long axis of framework grains that were selected using a point count grid. 2376 sets of core measurements included porosity and Klinkenberg permeability at in situ stress and 270 DST pore pressure measurements were used in this study. 89 Scanning electron microscopy (SEM) images were observed to examine the relationship between overpressure and microscopic textures.

## 4. Results

#### 4.1 Sandstone composition and grain size

The Es Formation had been deposited through an environmental change of fluvial /delta – shallow/deep lacustrine – shallow lacustrine/ delta – lacustrine (Zhu et al., 2008). The changes formed four distinct members and sandstones are mainly encountered in the second and fourth members in Es Formation. Thin sections and casting thin section observations suggest the Es sandstones are mainly well sorted lithic arkose and Feldspar litharenite, and a small portion of arkose (Fig. 4a, red circles). The rock fragments are mainly from igneous and metamorphic rocks. The Ed Formation was dominantly formed in lacustrine environment with

delta sediments in the slopes. The Ed sandstones comprise lithic arkose and feldspar litharenite, in which lithic arkose takes up slightly more portions (Fig. 4a, blue filled circles). Es and Ed sandstones are generally fine-medium grained. The sandstones are coarser in Es Formation than which in Ed Formation (Fig. 4b).

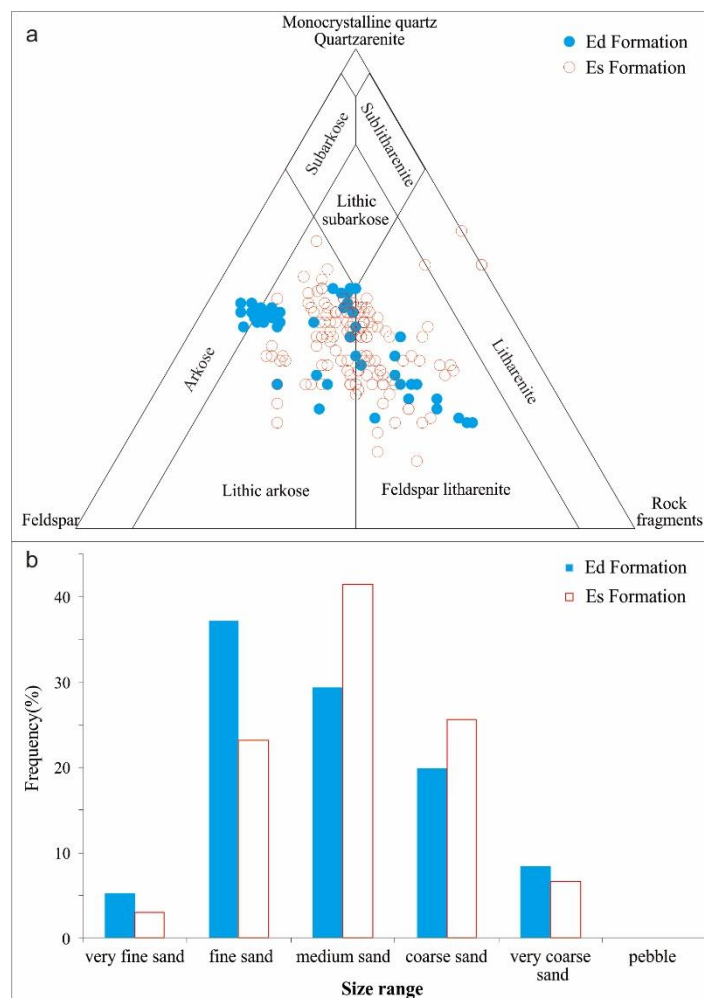


Figure 4. Composition and grain size of the Es and Ed sandstones in Bozhong Depression.

#### 4.2 Porosity and permeability

Core measured sandstone porosities in Es Formation range 10 ~ 30 % from the depth of 2600 m; in Ed Formation they value 8~ 35% from the depth of 1700m (Fig. 5). The porosities in Es and Ed Formations generally demonstrate a decreasing trend versus depth, but off-trend high porosities are encountered in both formations. The porosity can reach 30% at the depth of ~4300 m (13124 ft.), which deviate from the regional porosity trend significantly. As the sandstone type and grain size don't vary substantially in the two formations, pore pressure is taken into account to explain the generation and maintaining of the off-trend high porosities in deep reservoir. Seen from the correlation of the porosities of the entire sandstone reservoir and porosities in the overpressured intervals, the off-trend high porosities predominantly fall in the



overpressured intervals. Klinkenberg permeability in Bozhong Depression ranges 0.001 ~ 7000 mD and correlates well with porosities, suggesting the porosity can be relied solely to estimate the reservoir quality (Fig. 6).

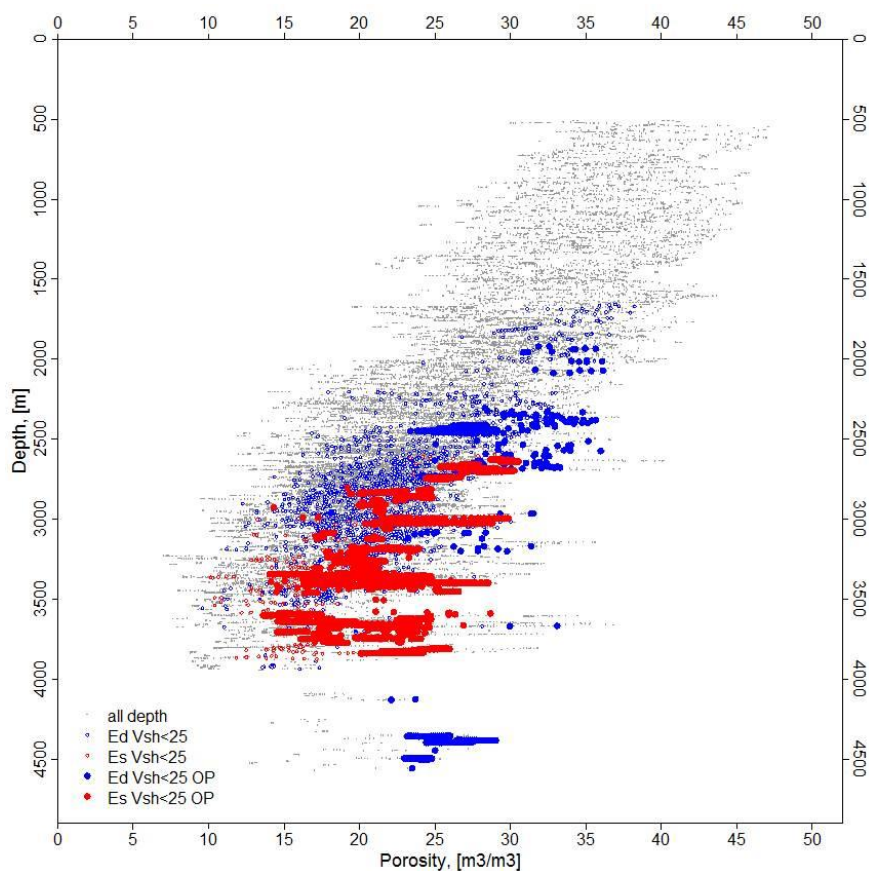


Figure 5. Porosity versus depth in Bozhong Depression.

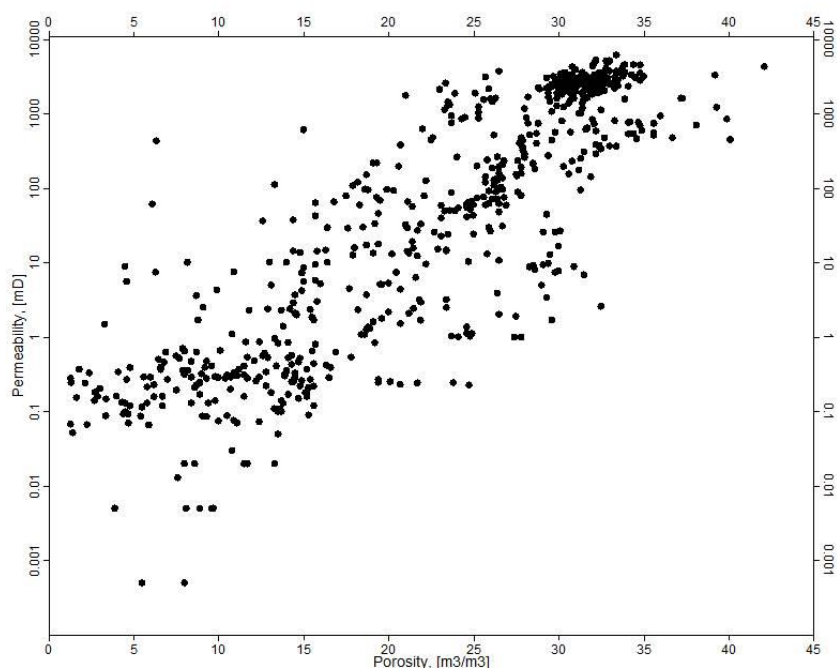


Figure 6. Porosity-permeability correlation in Bozhong Depression.

### 4.3 Pore pressure characteristics in Bozhong Depression

Vertically, DST data shows there are abnormally high pressures in Es and Ed Formations in this area (Fig. 7). Generally, the overpressure onset can be recognised from ~2500 m (8202 ft.) in depth and get the greatest magnitude between 3500m and 3800m (11483~12467 ft.). Pore pressure in Ed Formation reaches 59.63 MPa (8647 psi) at the depth of 3650 m (11977 ft.), with the overpressure coefficient (the ratio of pore pressure to hydrostatic pressure) of 1.65; in Es Formation, the maximum measured pore pressure, 61.46 MPa (8912 psi), occurs at the depth of 3768 m (12363 ft.). Wells revealed overpressure distribute around the Bozhong Depression (Fig. 8). There is no well drilled in the deep sag centre where current water depth of Bohai Sea reaches 85 m (279 ft.) or deeper, hence the regional distribution of overpressure was estimated from basin modelling.

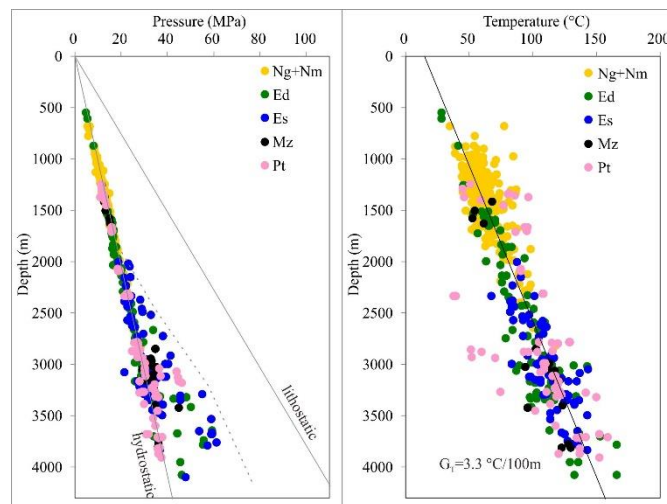


Figure 7. Measured data of pressure and temperature versus depth.

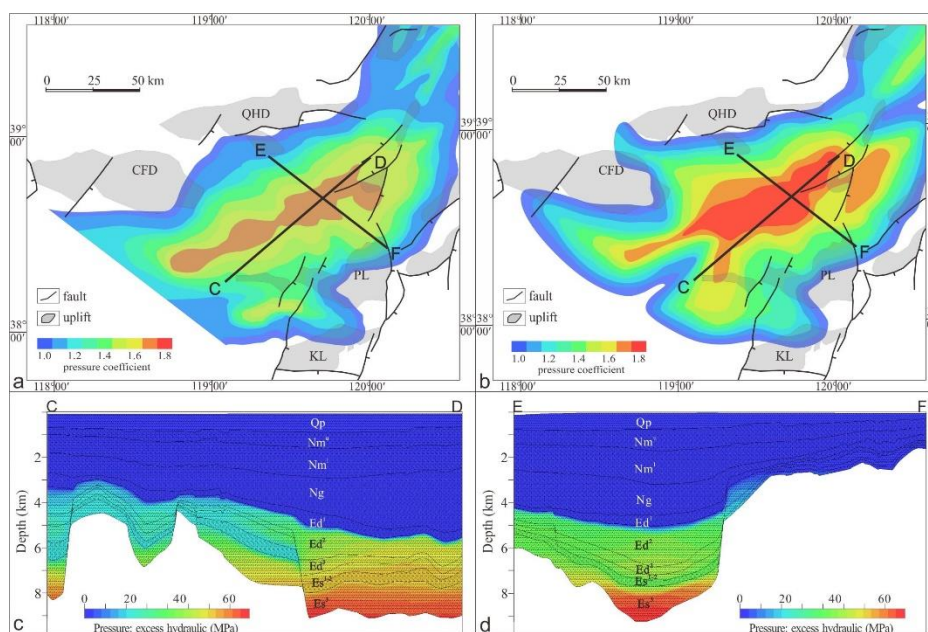


Figure 8. Distribution maps and profiles of overpressure in Bozhong Depression.

#### 4.4 Microscopic characteristics

Micro analysis of porosity has been carried out to analysis the porosity preservation situations in normally compacted sandstones and overpressured ones. SEM photos of the sandstone samples are differentiated by their stratum and sedimentary facies. When compared, the micro porosities of sandstones in same stratum and same facies show significant difference as the pore pressure conditions are different

In Ed Formation, sample ① is taken from the depth of 2888 m (9475 ft.), the excess hydrostatic pressure is 8MPa (1160 psi); Neutron porosity at this depth is ~27% (Fig. 9a). In the SEM image, primary pores can be seen and the cementation is not severe. Cements are quartz, illite, and some kaolinite (Fig. 9b, ①).

Sample ② is taken from the depth of 2702 m (8866 ft.), the excess hydrostatic pressure is 2 MPa (290 psi); Neutron porosity at this depth is ~17% (Fig. 9a). In the SEM image, primary pores are filled by illite, kaolinite and some carbonate (Fig. 9b, ②).

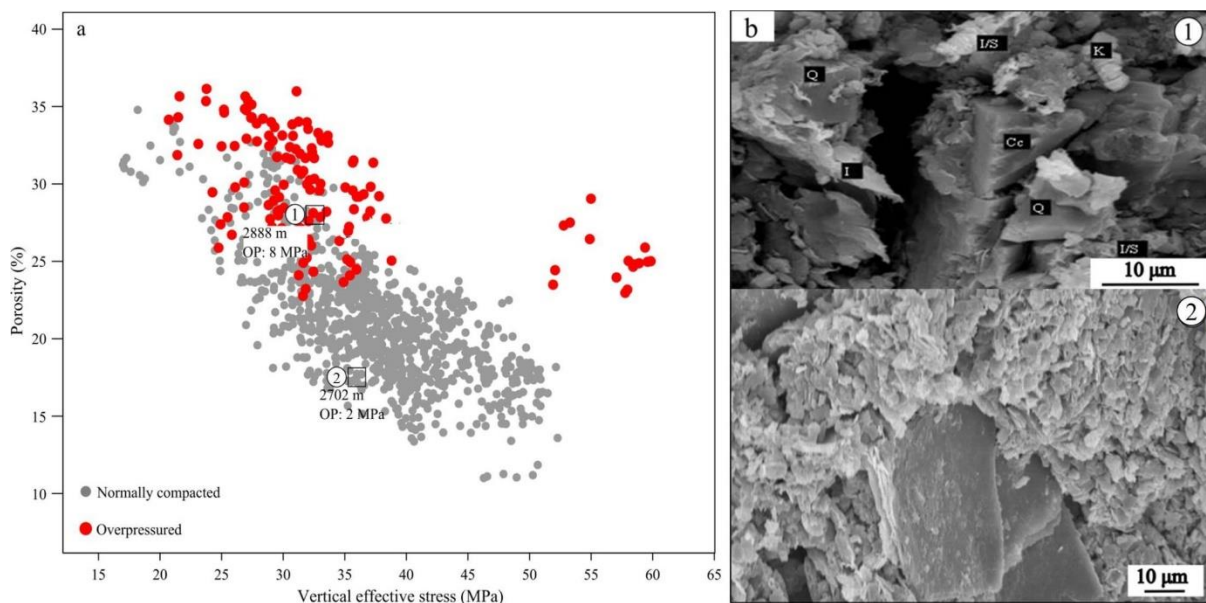


Figure 9. The SEM images of Ed sandstones within different pore pressure horizons.

Unlike Ed Formation which is overpressured in deeper part, Es Formation is generally overpressured. In Es Formation, sample ① is taken from the depth of 3002 m (9850 ft.), the excess hydrostatic pressure is 10 MPa (1450 psi); Neutron porosity at this depth is ~23% (Fig. 10a). In the SEM image, primary pores can be seen and the cements are quartz, illite, and some kaolinite (Fig. 10b, ①).

Sample ② is taken from the depth of 3704 m (12153 ft.), the excess hydrostatic pressure is 23 MPa (3335 psi); Neutron porosity at this depth is ~24% (Fig. 10a). In the SEM image,

chlorite grain coats may help preserve the primary pores (Fig. 10b, ②). Though it is deeper, the porosity maintains high compare to other samples.

Sample ③ is taken from the depth of 3430 m (11254 ft.), the excess hydrostatic pressure is 9 MPa (1306 psi); Neutron porosity at this depth is ~17% (Fig. 10a). In the SEM image, primary pores are filled by illite and kaolinite (Fig. 10b, ③). The overpressure magnitude is relatively small considering its depth when compare to sample ①, and the porosity is smaller. Sample ④ is taken from the depth of 3091 m (10141 ft.), the excess hydrostatic pressure is 5 MPa (725 psi); Neutron porosity at this depth is ~20% (Fig. 10a). In the SEM image, grains are cemented by calcite and some kaolinite (Fig. 10b, ④).

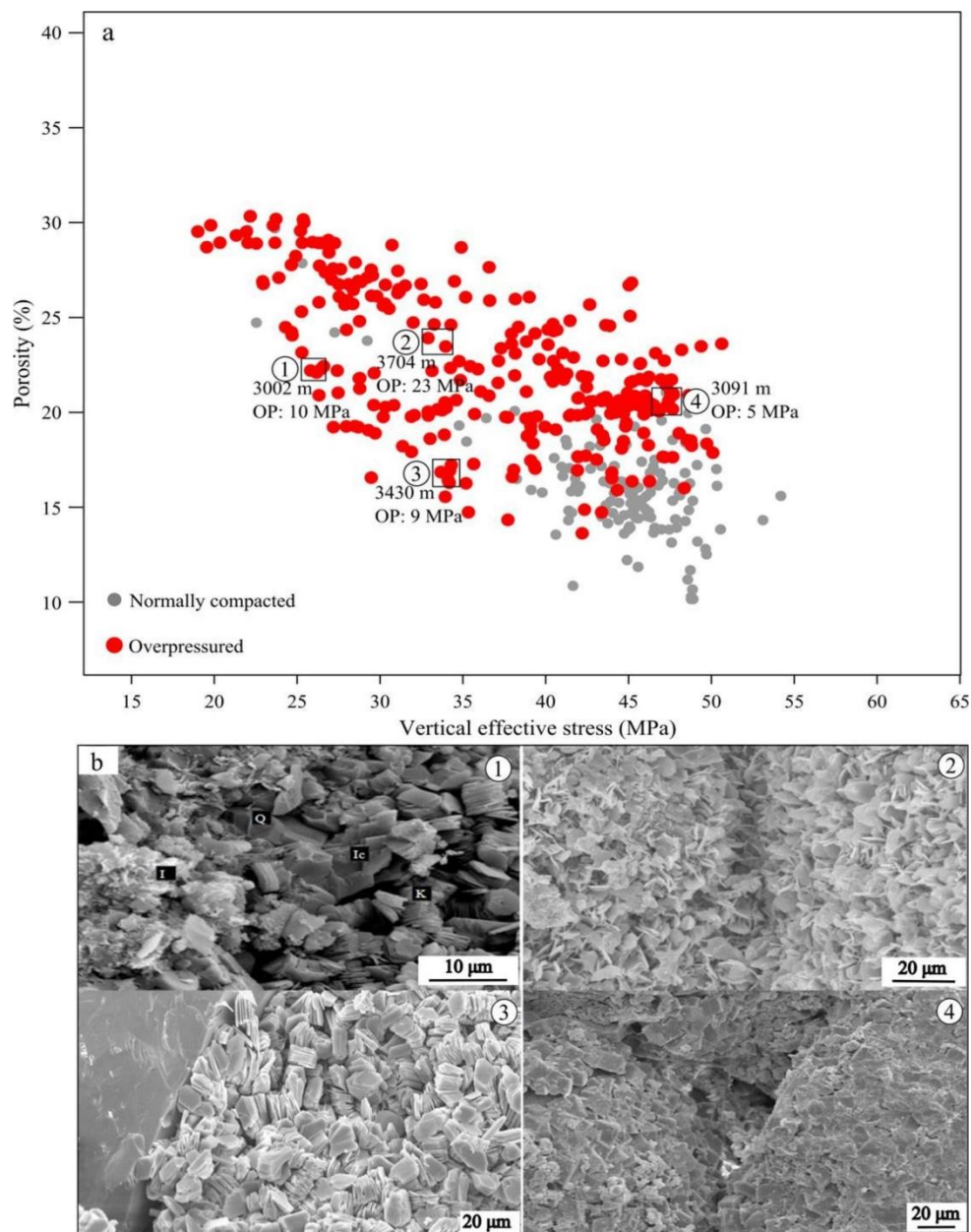


Figure 10. The SEM images of Es sandstones within different pore pressure horizons.



## **5. Discussion**

### **5.1 The origin of overpressure**

As stated in the geological settings, Es and Ed Formations are of great thickness in Bozhong Depression. Sedimentation rates of these two formations are relatively high, averaged over 200 m/Ma, with the highest reached 525m/Ma (see section 2.3). In normal compaction basin with similar age and lithology, the sedimentation rate is usually less than 100 m/Ma (Ibach, 1982; Katz, 2005). The rapid sedimentation of Es and Ed prevented pore pressure in and underneath Lower Ed to dissipate during the burial processes. This disequilibrium compaction gradually accumulated overpressures in Es and Ed Formations. The estimation of pore pressure evolution shows the overpressure (pore pressure exceeds hydrostatic pressure) primarily emerged during the deposition of the middle member of Ed Formation ( $E_{3d}^2$ ) (see Fig. 8).

Hydrocarbon generation is considered to be the second cause of overpressure. The source rocks in Es and Ed Formations were buried deep during the rapid burial which may have accelerated their maturation and generation behaviour. Source rocks in Es and Ed Formations have a vitrinite reflectance ( $R_o$ ) values of 0.6% or higher under the depth of 2500 m (8203 ft.).

### **5.2 Vertical effective stress – porosity relationships**

Since the overpressure in Bozhong Depression is mainly caused by disequilibrium compaction, mechanical compaction may have controlled the primary porosity preservation in sandstones. We used equation derived from Terzaghi's effective stress principle to investigate the VES (Nur and Byerlee, 1971; Tuncay and Corapcioglu, 1995). The relationship of porosity and vertical effective stress (VES) is employed in this research to investigate the process of mechanical compaction and its effect on the porosities. Sandstone porosities in Es and Ed Formations generally show a decreasing trend while the VES increases (Fig. 11, first column). The porosities in overpressured horizons are on the trend but a bit higher at same VES compared to which in normal pressured horizons, which may indicate overpressured sandstones have better porosity than normally compacted ones at the same depth.

The compaction rate of sandstones varies significantly from facies to facies. The finer grained sediments can be compacted relatively faster and easier than coarse grains. To eliminate the facies variation effect in compaction process, shale content (Vsh) is introduced to investigate the VES – porosity relationship in similar sandstones. Considering the facies evolution in Bozhong Depression, sandstones have Vsh less than 25% formed in shallow lacustrine or slope, Vsh less than 15% mostly occur in delta front. As in Fig. 11 (middle and right columns), sandstones with Vsh less than 15% show the most distinct and uniform

decreasing trend. The high pore pressure horizons, which are the low in VES, correlate to high porosities. This indicates overpressure helped preserving the primary porosity.

Some anomalously high porosity occurs in Ed Formation in a deep well (stays 25~30 % below 4300 m / Fig. 11, upper row). This porosity may be added by the secondary dissolution porosity.

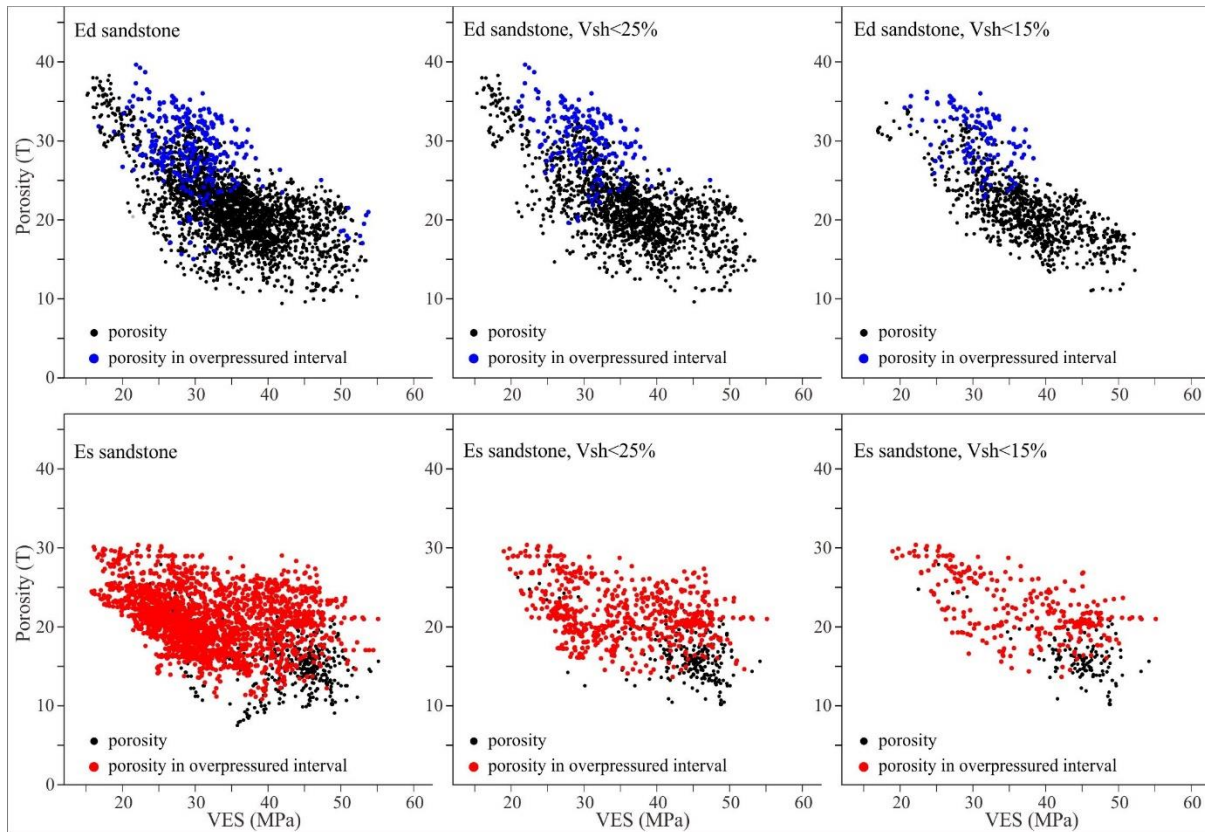


Figure 11. The relationship of porosity and vertical effective stress in Bozhong Depression.

### 5.3 Schematic model of the preservation effect of overpressure on sandstone porosity

Based on the above analysis, we have established a schematic model which illustrate the vertical effective stress and sandstone porosity evolution (Fig. 12). The intention of this model is to provide a quantitative reference for the relationship of overpressure, pore structures, porosity, and VES. For normally compacted sandstone reservoirs which consists mainly of quartz and feldspars and have initial primary intergranular porosity of ~30%, the initial VES would be ~20 MPa. The contact of grains were point contact, and cementation was weak. With the burial depth increasing, the VES increased. With increasing VES, the contact of matrix grains in sandstones became tighter, from point contact to line contact. The primary intergranular pores became smaller or even vanished. When VES reached ~40 MPa, the primary intergranular porosity would decline to less than 15%. However, the primary intergranular porosity in undercompacted reservoir (having an overpressure magnitude of ~20

MPa) can retain 25% at the similar depth. Undercompaction induced overpressures would be preserved in the matrix unless deformed afterwards, hence they can resist the stress act upon sandstone grains, keeping the VES from increasing. Therefore, the compaction between matrix grains and reservoir porosity were protected by overpressure. The primary intergranular porosity preserved by overpressure can be more than 10% higher than normally compacted porosity under the same condition of depth and temperature.

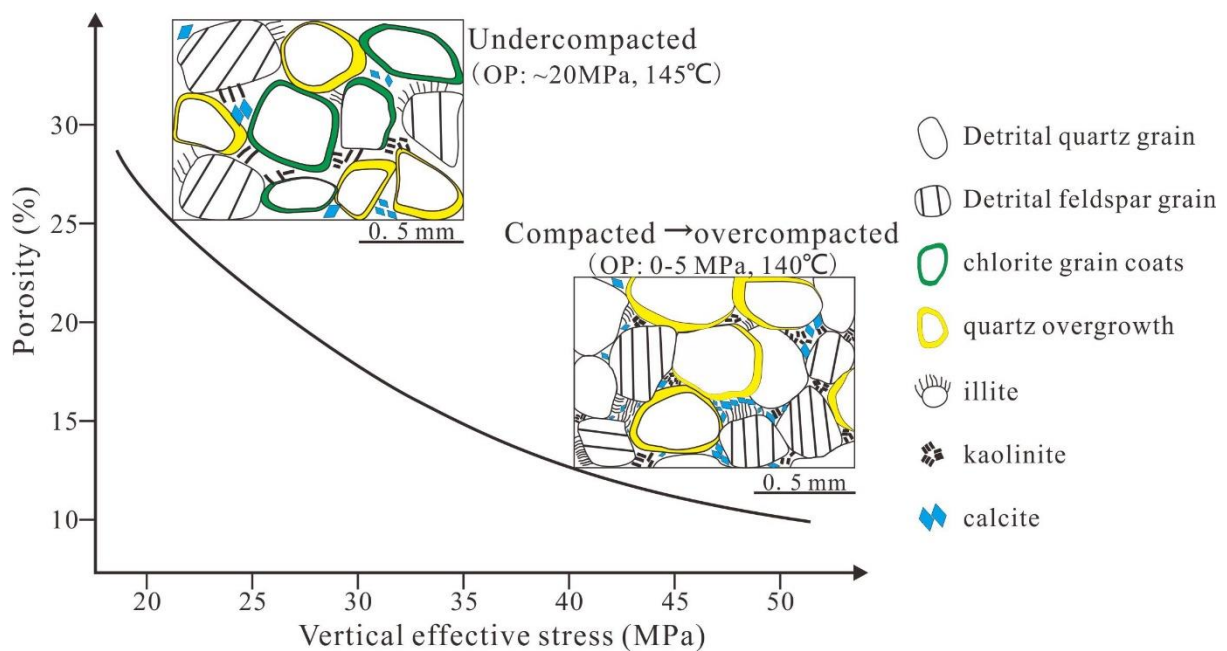


Figure 12. The schematic diagram of the relationship between VES and porosity.

## 6. Conclusion

Extensive overpressure has been encountered in Bozhong Depression of offshore Bohai Bay Basin. The overpressure is mainly confined in the Es and Ed Formations, and the pore pressure can reach ~60 MPa (8700 psi) at the depth of ~3700 m (12140 ft.) according to the measured data. Disequilibrium compaction is identified as the main mechanism of overpressure generation in this area. Hydrocarbon generation has added to the amount of overpressure at the present day.

Reservoir quality of sandstone in the Es and Ed Formations is variable but there are off-trend high porosities which can be up to 30% at the depth of ~4000 m (13124 ft.). Almost all of these off-trend high porosities are recorded in the intervals with overpressure. Porosity-vertical effective stress analysis and the micro pore structures validate the positive effect of overpressure on high porosity preservation. The primary intergranular porosity preserved by overpressure can be more than 10% higher than normally compacted porosity under the same condition of depth and temperature.

## Acknowledgments

This work was supported by the Fundamental Research Funds for the Central Universities, China University of Geosciences (Wuhan), and China National Science and Technology Major Project (No. 2016ZX05006-003-001). Xiao Wang's visiting study in Durham University was supported by China Scholarship Council (No. 201406410047).

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458 **Figure captions**

459 Figure 1. Location and structural distribution of Bozhong Depression.

460 Figure 2. Summarized stratigraphic columns of offshore Bohai Bay Basin.

461 Figure 3. Burial and thermal history of Bozhong Depression.

462 Figure 4. Composition and grain size of the Es and Ed sandstones in Bozhong Depression.

463 Figure 5. Porosity versus depth in Bozhong Depression.

464 Figure 6. Porosity-permeability correlation in Bozhong Depression.

465 Figure 7. Measured data of pressure and temperature versus depth.

466 \*The hydrostatic pressure gradient in this area is 10 MPa/km (0.442 psi/ft).

467 \*Overlapped depth of different stratum is due to the difference of structural location.

468 Figure 8. Distribution maps and profiles of overpressure in Bozhong Depression.

469 Figure 9. The SEM images of Ed sandstones within different pore pressure horizons.

470 Figure 10. The SEM images of Es sandstones within different pore pressure horizons.

471 Figure 11. The relationship of porosity and vertical effective stress in Bozhong Depression.

472 Figure 12. The schematic diagram of the relationship between VES and porosity.